USE OF HIGH RESOLUTION PATHFINDER SST DATA TO DOCUMENT CORAL REEF BLEACHING*

M. A. Toscano
NOAA/NESDIS/ORA/ORAD
Silver Spring, MD USA

K. S. Casey
NOAA/NESDIS/NODC
Silver Spring, MD USA

J. Shannon
U. S. Naval Academy
Annapolis, MD, USA

ABSTRACT

Mass coral bleaching has been observed throughout the tropical oceans immediately following periods of thermal stress, in concert with other known causes. While water temperatures monitored *in situ* best document the relationship of thermal stress to bleaching, most reef sites have limited to no *in situ* data. For such areas, high-resolution satellite-derived SSTs provide valuable time series data and quantify thermal anomalies and their timing vs. onset of bleaching. The availability of 9km NOAA/NASA Oceans Pathfinder SST data (1985-2001), an internally consistent, calibrated SST database at reef scale resolution, allows us to assess the accuracy and usefulness of satellite SST data to document past conditions in reefs.

Statistical analyses of SSTs combined with available *in situ* temperatures from Caribbean and tropical Pacific locations indicate that 9km SSTs for specific sites, and for the 3x3 pixel means surrounding each site, are highly correlated to *in situ* temperatures. Biases are tied, wherever possible, to local physical causes. Pathfinder SSTs accurately represent surface field temperatures with predictable exceptions, and therefore have great potential for assessing temperature histories of remote, un-monitored reefs.

1.0 THERMAL STRESS AND CORAL REEF BLEACHING

Bleaching is the loss of algal symbionts (zooxanthellae) and/or their pigments from a coral (or other symbiotic animal) host, and occurs in response to environmental stressors which vary regionally and seasonally, and which may act singly or synergistically (Fitt et al. 2001). The most apparent and globally documented of these is thermal stress. Corals and other zooxanthellate reef organisms occupy a restricted temperature range (approximately 18-30ºC). In the summertime, water temperatures surrounding reefs normally approach local maxima and/or the upper thermal tolerance limits of many species (Jokiel and Coles 1990; Glynn 1993; Hoegh-Guldberg 1999). Sufficient and sustained positive temperature anomalies are deleterious to the coral-algal symbiosis, resulting in changes in photosynthesis reactions, production of damaging free oxygen radicals, and subsequent expulsion of the symbionts (reviewed by Hoegh-Guldberg, 1999). Prolonged bleaching results in coral mortality. For bleaching to occur in a particular area, thermal anomalies must exceed the local threshold, which lies between the highest locally-tolerated, non-bleaching temperature and the lowest temperature known to initiate bleaching in that area (Glynn 1996; Brown 1997). In general, SSTs >=1°C above local mean summer maximum temperatures, sustained over days or weeks, have been correlated with observed bleaching events (e.g. Jokiel and Coles 1990; Podesta and Glynn 1997; 2001).

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1.1 USE OF SST DATA TO PREDICT CORAL REEF BLEACHING

Goreau and Hayes (1994) first mapped “hot spot” anomalies in retrospect using monthly SSTs. In 1997, NOAA initiated twice-weekly, global “HotSpot” anomaly mapping at 50km resolution (http://psbsgi1.nesdis.noaa.gov: 8080/PSB/EPS/SST/climohot.html). HotSpot thresholds were based on a satellite-only maximum monthly mean (MMM) climatology (MCSST, 1984-1993) computed from nighttime sea surface temperatures (SSTs; Strong et al. 1997). Mapped HotSpots (particularly those exceeding the MMMs by 1°C) predicted areas of thermally-induced bleaching worldwide during the 1997-1998 El Niño.

Recently, Toscano et al. (in press) revised the MMM climatology and improved HotSpot mapping resolution and accuracy using 9km NOAA/NASA Oceans Pathfinder SST data (Kilpatrick et al. 2001; Kearns et al. 2000), a re-calibrated AVHRR dataset derived from the Pathfinder version of the non-linear SST (NLSST) algorithm, spanning 17 years (1985-2001). Pathfinder data provide long time series of cloud-cleared temperatures that are internally consistent over time. The high resolution of the Pathfinder data makes them more useful to reef studies than operational 1º or 0.5º data (e.g. Mumby et al. 2001; Davies et al. 1997). SSTs calculated by the Pathfinder algorithm are calibrated by coincident buoy matchups and exhibit small biases, both globally (+0.1ºC±0.5) and in the tropics (-0.1ºC to -0.2ºC). The Pathfinder algorithm is not without potential limitations, however. In the tropics, the algorithm slightly under-predicts SSTs due to under-correction for atmospheric water vapor and cloud effects between 20ºS-20ºN (Kilpatrick et al. 2001). Additionally, the global Pathfinder algorithm may not account for region-specific deviations, and may discard certain useable data via cloud clearing routines and specific temperature thresholds in quality testing. Also, the 9km resolution may still be too coarse to pinpoint conditions in small reef sites, and a coarse (pre-processing) land mask has effectively eliminated SSTs from numerous pixels in coastal zones and near reefs between 1985 and 1998 (Kilpatrick, Halliwell, and Kearns, pers. comm.). In these cases neighboring pixels obtained by retrieving SSTs from a 9-pixel grid centered on the desired location are used. While only small differences are seen between SSTs from a single target pixel and the 3x3 pixel grid, the averaging of data from 9 (or fewer) pixels further reduces the record of actual variability in the reef environment.

Because of these potential limitations and the fact that the Pathfinder algorithm is designed to minimize global biases and may have larger regional errors, Pathfinder SSTs are tested against available *in situ* records at specific reef locations to verify their applicability in the highly variable coastal zones. If Pathfinder SSTs are highly correlated to the field data from these monitored localities, and exhibit minimal SST-*in situ* differences, they can be an invaluable resource for studying the temperature histories of reefs in remote or otherwise un-monitored regions, and provide longer-term temperature histories for areas with short-term *in situ* monitoring. Correlated time series of *in situ* and Pathfinder SSTs from 1985-2001 are examined along with high-resolution HotSpot thresholds for field sites from 9-km Pathfinder data (average of daytime and nighttime maximum pentad mean (MPM) climatological SSTs over the 9-yr baseline period 1985-1993; Casey and Toscano in prep.). Bleaching thresholds are set at 1°C above the local MPM value, which represents the local mean summer maximum temperature. MPM values and bleaching thresholds may be used to calculate the magnitude of thermal anomalies and their rate of change in association with occurrence and severity of bleaching.

2.0 REGION AND LOCALITY COMPARISONS

2.1 CARIBBEAN

2.1.1 Florida Keys

In the Florida reef tract, warm season SST data appear to match and correlate well with *in situ* temperatures recorded at 1m depths on NDBC buoys (http://seaboard.ndbc.noaa.gov/) and by SeaKeys CMAN instruments (http://coral.aoml.noaa.gov/cman/cman_menu.html), located east of the Keys along the outer reef tract, and the 9km HotSpot thresholds accurately account for bleaching years (Table 1; Figure 1; Causey 2001). In winter, large, short-lived, SE-moving cold-water excursions are recorded correctly by *in situ* sensors, but not by the 9km satellite data. Mean southeastward flow from the SW Florida shelf towards the reef tract, through tidal channels in the Florida Keys, is driven year-round by sea-level height differences and winds. In December, January and February, winds from the N and NW increase subtidal flows of cold SW Florida shelf waters southeast toward the reef tract (Lee et al. 2002). Additionally, SE-flowing chilled, turbid water masses induced by episodic cold front passages have been recorded by 1km AVHRR SST data (Walker et al. 1987). For reefs sheltered from tidal exchanges, cold air outbreaks are also recorded by *in situ* sensors (e.g. Molasses Reef, Figure 1) but *not* by Pathfinder data.

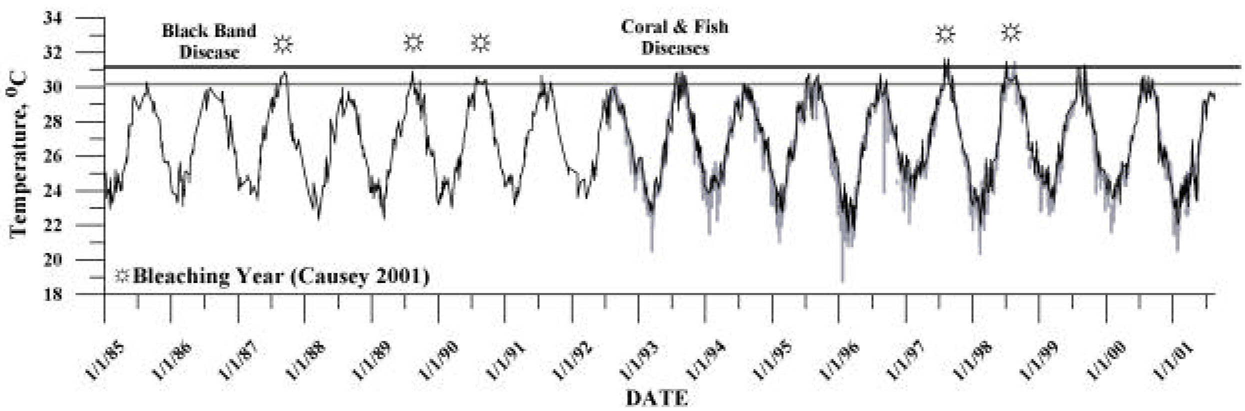

Figure 1. Molasses Reef, Florida Keys: *in situ* time series (gray curve) showing actual cold water events that are not reproduced by the Pathfinder data (black curve). The 9km MPM value (gray horizontal line) and bleaching threshold (black line) identified years in which the reef experienced bleaching or other heat-related perturbations.

The lack of matchup between *in situ* recorded cold excursions, which have known physical causes, and 9km Pathfinder data may be due to the resolution of the satellite SST data compared to the buoy locations, or to the cloud-clearing and data quality testing routines in the SST processing. Cloud masking in SST processing may cause such data to be discarded, thus eliminating any record of such events from the Pathfinder SST time series.

2.1.2 Bahamas

Bahamas sites represent greater environmental variation than Florida Keys sites. Two deep sites in Exuma sound, exposed to onshore winds and open water, show remarkably good matchups and correlations to SSTs with no obvious deviations (Table 1). For shallow sites, as in Florida, cold events are not always recorded by Pathfinder. Warm *in situ* temperatures are slightly underestimated by the SSTs. The Rainbow Gardens sensor at -4m MSL reveals warmer waters below the surface during the summer, likely due to the formation of warm, hyperpycnal water on the Great Bahama Bank, and to decreased wind forcing of flood tidal flows (Smith 2001).

SST minus *in situ* differences (Table 1) vary with reef location. At deep sites, Pathfinder SSTs are slightly warmer than *in situ* temperatures in late spring/early summer. SSTs become cooler than *in situ* deep water in late summer - late fall due both to along-shelf transport of warm hyperpycnal bank water and to the seasonal downwelling of warmer surface waters (Smith 2001). At shallow sites, late spring/summer SSTs are cooler than *in situ* temperatures in sheltered areas, and slightly warmer in more open shallow areas subject to tidal currents.

2.1.3 Belize

Coral populations in all habitats in Belize bleached as a result of elevated SSTs in the summer and fall of 1998 (Koltes et al. 1998; Aronson et al. in press). Daily averages of Pathfinder SSTs for reefs at Carrie Bow Cay and Twin Cays were highly correlated with daily averages of *in situ* temperatures measured at each (Table 1). *In situ* temperatures from these sites were slightly warmer than SSTs. We still note a few cold excursions in local winter temperatures that are not recorded by Pathfinder. Both sites produced high Pearson r values, allowing for analysis of a nearby site, Channel Cay, which had no *in situ* temperatures. Pathfinder SSTs for Channel Cay exceeded local HotSpot and bleaching thresholds for 23 d in late summer, peaking at 4.1 °C above the HotSpot threshold.

Table one summarizes correlation analyses and bias statistics for Caribbean sites. Pearson r values are uniformly high, both for the specific reef pixel and the 9-pixel surround area. Biases are shown below the correlations.

Table 1. Correlation of 24 hr Mean *in situ* Temperatures vs Pathfinder SST, Caribbean Sites ($p<0.001$ in all cases).

Site		**Depth (m)**	**Day 9-pixel**	**Night 9-pixel**	**D/N 9-pixel**	**Day (Reef)**	**Night (Reef)**	**D/N (Reef)**
FL Keys:	Dry Tortugas	1	0.96	0.97	0.97	0.96	0.98	0.97
	Fowey Rocks	1	0.94	0.93	0.95	0.95	0.94	0.96
	Long Key	1	0.91	0.89	0.92	0.93	0.98	0.98
	Molasses Reef	1	0.96	0.95	0.97	0.96	0.96	0.98
	Sand Key	1	0.94	0.94	0.95	0.94	0.96	0.96
	Sombrero Reef	1	0.96	0.97	0.97	0.95	0.95	0.97
Bahamas:	Adderly Dropoff	33	0.88	0.89	0.91	-----	-----	-----
	Barracuda Rocks	2	0.97	0.96	0.97	0.97	0.96	0.98
	LSI Dock	3	0.93	0.92	0.94	-----	-----	-----
	Rainbow Gardens	4	0.94	0.94	0.96	0.94	0.95	0.96
	Shark Rock	3	0.94	0.94	0.96	-----	-----	-----
	South Perry	16	0.93	0.93	0.95	-----	-----	-----
Belize:	Carrie Bow Cay	2	0.85	0.84	0.87	-----	-----	-----
	Twin Cays	1.4	0.87	0.83	0.85	-----	-----	-----

Biases: 9-pixel SST minus *in situ* temperature (Standard Deviation)

		Day	**Night**	**Day/Night**
Florida Keys:		0.40 (1.03)	-0.09 (1.01)	0.12 (0.89)
Bahamas:	Deep Sites	0.36 (0.84)	-0.06 (0.79)	0.11 (0.71)
	Shallow Sites	-0.21 (0.76)	-0.54 (0.77)	-0.33 (0.64)

2.2 PACIFIC

2.2.1 Panama

Podesta and Glynn (1997, 2001) documented cold *in situ* SST residuals from the seasonal cycle in the Gulf of Panama, resulting from seasonal upwelling between March and April, when the ITCZ shifts south and northeasterly trades intensify. Prevailing northerly winds displace Gulf of Panama waters offshore, causing upwelling of cold, nutrient rich water. During the 1998 El Niño, these normally cold anomalies became positive and persisted through June (Figure 2). Figure 2 indicates that during previous years, the upwelling is not normally recorded by Pathfinder. Correlation analysis (Table 2) gives better results for night SST data than for Day SST data in this case. Pathfinder Day SSTs account for the *in situ* peak temperatures, but neither night nor day SSTs account for the cold *in situ* upwelling features. Cloud masking may eliminate some of these SST data, however on clear days the SSTs still do not pick up the cold temperatures. Resolution could affect SSTs - the targeted pixel for Naos was masked, hence surrounding pixels (less than 9) were used.

2.2.2 Galapagos

The relationship of *in situ* temperatures to SSTs in Academy Bay, Santa Cruz Island, Galapagos, is similar to Florida's in that cold events in the field are not recorded in the Pathfinder SST data. Again, the confounding factors include quality assurance procedures or resolution. If the cold events are highly localized (in tidal channels, for example), the resolution may cause of the lack of matchups. Clear days during cold events produce SST data that are up to 2 degrees warmer than the *in situ* data, suggesting a combination of resolution and quality control problems. Pearson r values (Table 2) are very high despite the warm SST biases in winter.

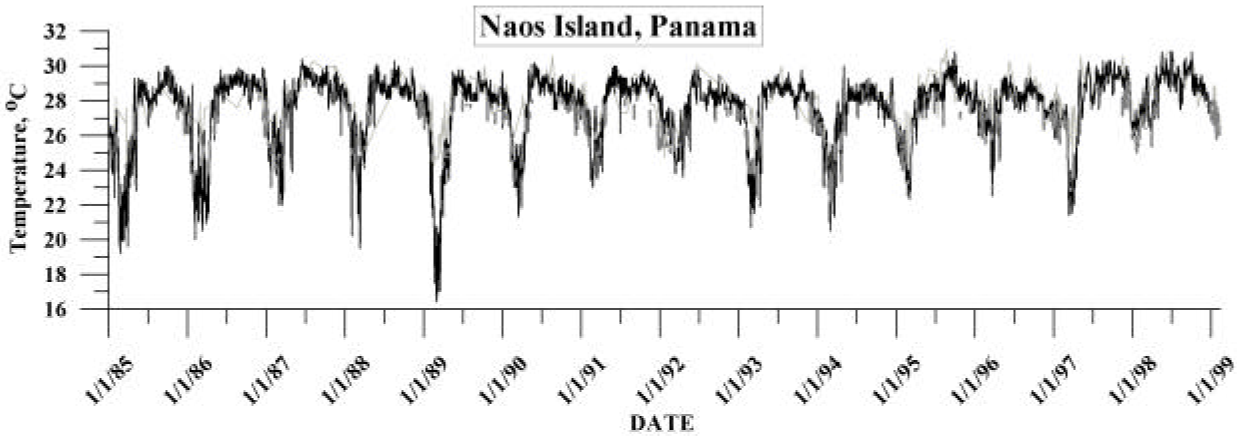

Figure 2. Time series of SSTs (Day =light gray curve, Night =dark gray curve) and *in situ* temperatures (black curve). Note the cold upwelling in *in situ* data (except during 1998) but not in Pathfinder data.

2.2.3 Great Barrier Reef

In general, Great Barrier Reef (oceanic) sites, spanning over 10º of latitude, are well matched to the SST data (Table 2), with no major warm or cold excursions, although seasonal SST-*in situ* differences of up to 2ºC exist in some shallow areas. These sites are widely separated, hence discussion of each is beyond the scope of this paper.

2.2.4 Fiji

The south-western Pacific island countries, largely unaffected by mass coral bleaching during the intense El Niño of 1998, experienced mass bleaching in 2000 during the subsequent strong La Niña (Cumming et al. in press). Figure 3 illustrates the link between high temperatures and La Niña conditions (1988-89, 1994-97, 1999-2000). Anomalously warm conditions seem to occur consistently within 2-3 years of major El Niño events, over the time frame of the SST data (1985-2001). *In situ* daily average temperatures (1996-2000) correlate well to daily SSTs, with no major excursions unaccounted for. Pearson r values are uniformly high (Table 2); for the SST time series pre-dating 1996, SST data are judged to be accurate for hindcasting thermal histories in southern and eastern Fiji.

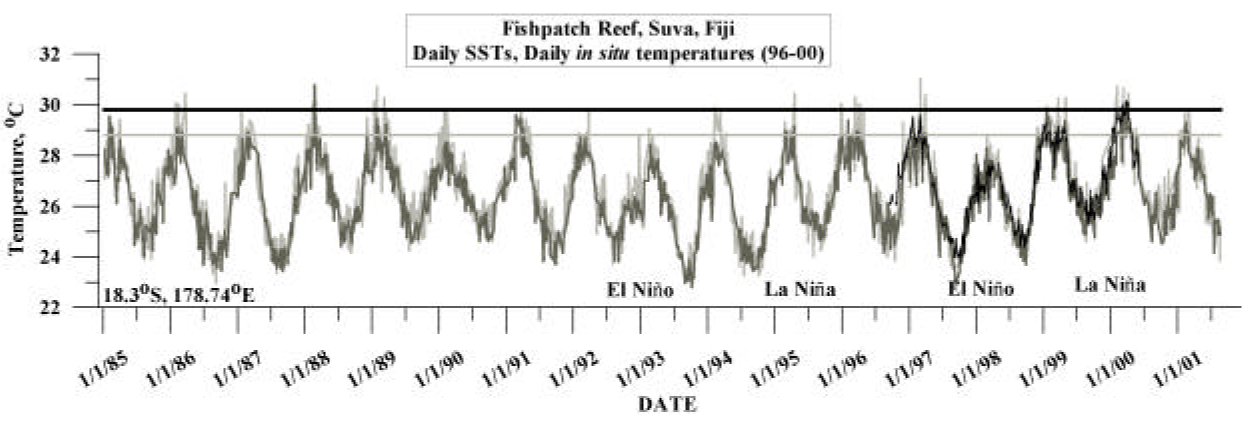

Figure 3. SST time series for Fishpatch Reef, Suva, Fiji. *In situ* temperatures (black curve) match and correlate well to SSTs (light gray curve=Day, dark gray curve = night). Past bleaching events can be hindcast using these SSTs and the 9km MPM/HotSpot and bleaching thresholds (horizontal gray and black lines, respectively).

2.2.5 Palau

Widespread coral bleaching occurred in the Republic of Palau in 1998, in association with the 1997/1998 El Niño (Bruno et al. 2001). Weekly *in situ* temperatures were available for one site (Short Drop Off, 1 year), thus Pathfinder 9km SST time series for reef sites surrounding the Palau Islands were analyzed to evaluate this event. 1998 (Figure 4) was an anomalously warm summer, with SSTs above the MPM/HotSpot climatology values. SST data provided a useful time-series perspective on the 1998 bleaching season in the absence of *in situ* monitoring.

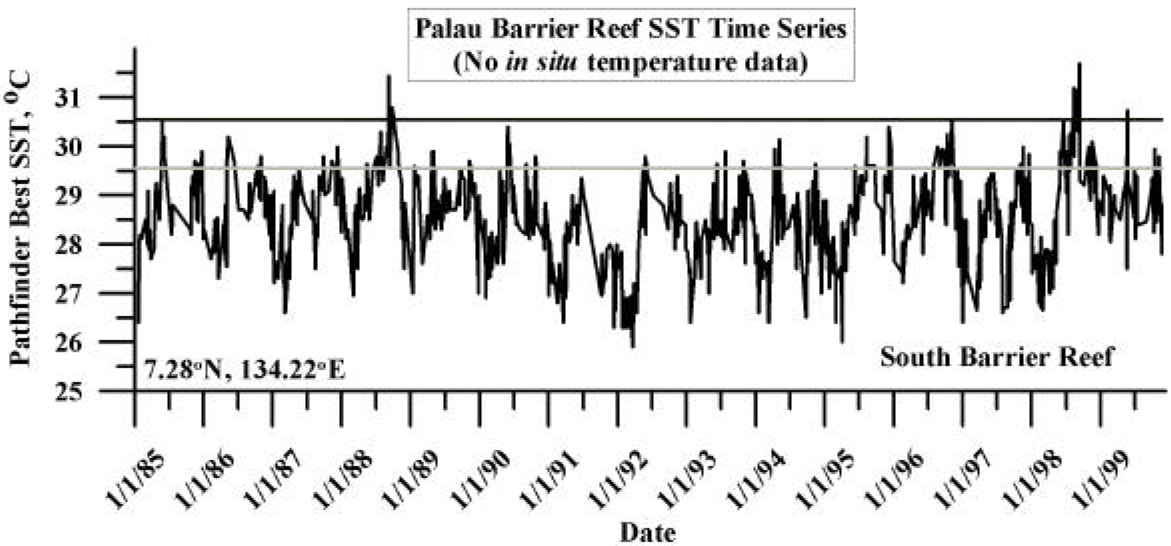

Figure 4. SST time series for the southern Palau barrier reef, showing anomalous 1998 temperatures.

Table 2. Correlation of 24 hr Mean i*n situ* Temperatures vs. Pathfinder SST, Pacific Sites ($p<0.001$ in all cases).

	Location	Day 9-pixel	Night 9-pixel	D/N 9-pixel	Day (Reef)	Night (Reef)	D/N (Reef)
Panama:	Naos Island	0.69	0.84		-----	-----	-----
Galapagos:	Academy Bay	0.94	0.94		-----	-----	-----
Fiji:	Suva	0.90	0.92	0.95	-----	-----	-----
GBR Sites:	Agincourt	0.95	0.96	0.97	0.94	0.96	0.96
	Cleveland Bay	0.98	0.97	0.98	-----	-----	-----
	Davies	0.95	0.94	0.98	0.97	0.95	0.97
	Hardy	0.97	0.96	0.98	0.97	0.96	0.97
	Myrmidon	0.94	0.94	0.96	0.94	0.94	0.96
	Nelly Bay	0.97	0.92	0.96	0.96	0.91	0.95
	Heron Island	0.86	0.83	0.85	-----	-----	-----

Biases: Pathfinder 9-Pixel SST minus *in situ* temperature averages (Standard Deviation)

Location	Day	Night	Day/Night
Panama :	0.65 (1.58)	-0.46 (1.06)	0.22 (1.23)
Galapagos:	0.33 (0.80)	0.08 (0.88)	0.30 (0.75)
G B Reef Sites:	0.06 (0.70)	-0.34 (0.78)	-0.25 (0.61)

3.0 DISCUSSION

In general, 9km Pathfinder SSTs match well with *in situ* temperatures. SSTs from both the target reef pixels and from the 9-pixel grids are highly correlated to field temperatures. In areas where the targeted reef site is obscured by the coarse land mask, data from unmasked neighboring pixels can be substituted with good results. Pathfinder's 9km resolution and quality testing and cloud clearing routines may be responsible for the lack of Pathfinder data during actual cold water episodes in areas that experience seasonal upwelling or cold weather effects on shallow water. Reasons for discarding Pathfinder data include failure of the comparison to the Reynolds climatological reference field for those localities and failure of a Uniformity test (Test 1) that seeks to detect contamination by small clouds in 3x3 pixel grids. Thus in areas of significant cold fronts, seasonal cold upwelling, or clouds, processed SSTs should be compared to local meteorological and oceanographic data to gain an understanding of their limitations for accurately describing local or regional cold events. In areas exhibiting such discrepancies, region-specific SST algorithms may be required to account for seasonal phenomena, water vapor regimes, and local hydrography.

4.0 CONCLUSIONS

Because available *in situ* data in and around reefs are geographically and temporally limited, these analyses suggest that 9km Pathfinder data can accurately estimate the SST time series for pre-monitoring years based on the correlation results from monitored years. Many remote reef areas have never been monitored *in situ*. Given the above results and caveats, in remote, un-monitored areas, 9km SST data can provide valuable time series perspectives at a resolution that is more applicable to reef-scale localities than other SST products.

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